# UPDATE ON THE U.S. ARMY TARDEC POWER AND ENERGY P&E SIL PROGRAM

Progress since the 6th AECV (June 2005 to Present)

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**Abstract**

The TARDEC Power and Energy (P&E) Program is described. The program continues to develop subsystems and full-scale systems, and to model and simulate performance for electric combat vehicles. The program began in 1997 as the Combat Hybrid Power System Program (CHPS) and continues today as the TARDEC P&E System Integration Laboratory (P&E SIL). The original goal to develop and test a full-scale, hybrid electric power system has not changed. To achieve that goal, the program developed a 100 percent hardware-in-the-loop P&E SIL and a sophisticated computational capability for modeling, simulation, and virtual prototyping. Progress updates in two basic focus areas are presented: 1) System Integration Laboratory; 2) Modeling, Simulation and Controls. Of special interest are two major P&E SIL upgrades since the last AECV in 2005 - a pair of 800 kW AC dynamometers have been installed; and a Hybrid Electric Reconfigurable Moveable Integration Testbed (HERMIT) has been built and installed. This paper briefly summarizes progress in all areas and, where relevant, mentions contributions to the Future Combat System (FCS) and other programs. The paper includes a summary of experimental accomplishments, an overview of HERMIT and its characteristics, and concepts for future work.

## INTRODUCTION

The Combat Hybrid Power System (CHPS)[1,2] initiative grew from an initial government research and development effort focused on integrating hybrid electric component technologies toward a specific vehicle platform and application. The program began in 1996 (1) as a joint program between the Army and the Defense Advanced Research Projects Agency (DARPA). The program was transitioned to a TARDEC program in 2000. The overall goals of the TARDEC P&E program are very similar to the original CHPS program, with a few additional goals. In 2004, the Army focused efforts on power and energy as well as hybrid power systems. The program was renamed the Power and Energy System Integration Laboratory (P&E SIL). The P&E SIL added the integration and testing of components for pulse power. The program has kept the focus of developing, testing and integrating hybrid electric power components for a notional manned ground vehicle (MGV). The P&E SIL goal is to integrate advanced P&E subsystems, to replicate operation in future vehicles, and to characterize system level performance and control. The P&E SIL provides the user a “form, fit, and function” environment to characterize power system capabilities.

In 2006, work began on integrating these components into a more practical envelope. The “envelope” developed was the Hybrid Electric Reconfigurable Moveable Integration Testbed (HERMIT). The HERMIT is a MGV like chassis frame used to integrate HEV components into an applicable space and vehicle environment and evaluate both system performance and space constraints. This testbed has been the focus of much of the recent work in the P&E SIL. Additionally, TARDEC has begun to use the P&E SIL to develop simulated hardware-in-the-loop (HWIL), Soldier-in-the-loop (SITL) duty cycles for an MGV sized hybrid electric combat vehicle. These duty cycles will provide a baseline for future component evaluation and system efficiency studies.

The time line in Figure 1 is updated from the previous AECV conference[3] to highlight more recent milestones. The Li-ion screen, Gen 1 Pulse Forming Network (PFN), PGU Testing and IGBT thermal characterization have been described before[4]. The “Hot Buck” is HERMIT. The MGV Testing and EGTL (Engine Generator Test Laboratory) testing was conducted for the FCS program and is not published yet. The Gen 2 PFN also appeared in earlier publications[5]. The previous

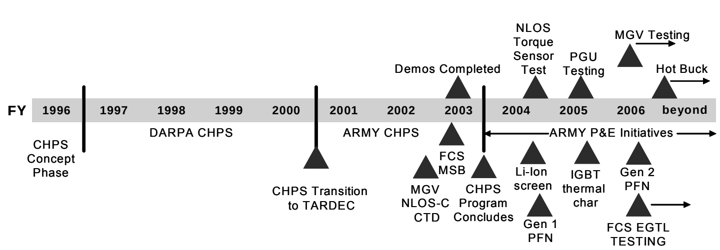


*Figure 1. Power and Energy Program Time Line*

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CHPS hardware and software resources remain intact and fully operational. The Power and Energy System Integration Laboratory (P&E SIL) located in Santa Clara, California, U.S.A., continues to operate daily. All the software assets such as end-to-end hybrid electric system models are continuously being used and upgraded. The remainder of this paper briefly summarizes progress in all areas and, where relevant, mentions contributions to FCS and other programs.

## P&E SIL EXPANSION

The P&E SIL underwent a major laboratory expansion in 2005 and 2006. The P&E SIL was reconfigured to enable the integration and testing of the advanced technologies in a relevant vehicle like environment, HERMIT. In effect, an entirely new P&E SIL was added adjacent to the existing P&E SIL. Figure 2 shows the changes. A 47-foot by 20-foot section was added to the P&E SIL building to provide room for new dynamometers and extra laboratory space. Two AVL APA 804-8, nominally 800-kW, bi-directional, AC dynamometers were installed as shown. Each dynamometer[6] has two output shafts, one directly connected to the motor, the other routed through a two-speed gearbox. The direct output shafts can provide 800-kW and 3,400-Nm torque continuously and 1,000-kW and 4,250-Nm for short durations (typically 15 seconds out of 60 seconds, limited by temperature rise.) Maximum direct output shaft speed is 8,000 rpm. The two available gear ratios from the other output shafts are 6.5:1 and 16.6:1 giving maximum speeds of 1,250 and 480 rpm. With the 6.5:1 gear ratio, maximum torque is 22,000-Nm continuously and 27,000-Nm for intermittent duty at low speeds. Power through the gearboxes is limited to 550-kW each thermally. The available range of torques and speeds allows the P&E SIL to simulate acceleration and braking of tracked vehicles up to the typical traction limit for gross vehicle weights in the 16 to 25-ton range, and steering at speeds up to 100-kph.

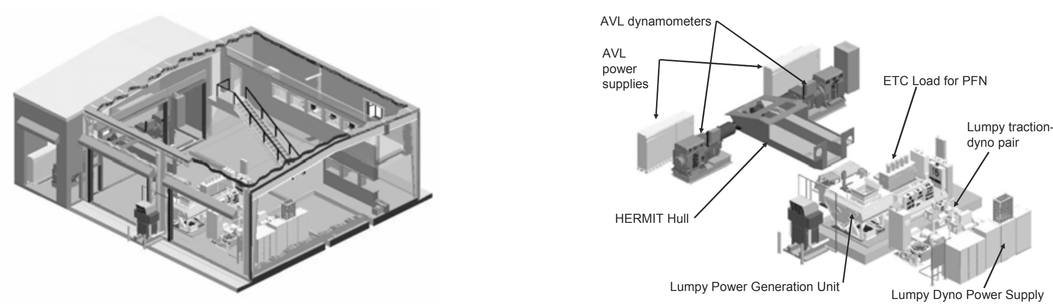


*Figure 2. P&E SIL Expansion*

The initial focus of the new dynamometers will be with the HERMIT, described later in this paper. The dynamometers will allow the HERMIT to be "virtually driven" providing realistic steering and terrain inputs into the power system. The resulting duty cycles or mission profiles, determined from these experiments will be used to evaluate the effectiveness of power management algorithms and to determine baseline fuel consumption. The duty cycle experiments are explained later in this paper. Figure 3 shows the basic dynamometer system set up. The dynamometers shows the basic dynamometer system shows the basic dynamometer system set up. The dynamometers are installed so a variety of tracked vehicle types can be easily evaluated. The P&E SIL will provide testing capability for the FCS program and HERMIT.

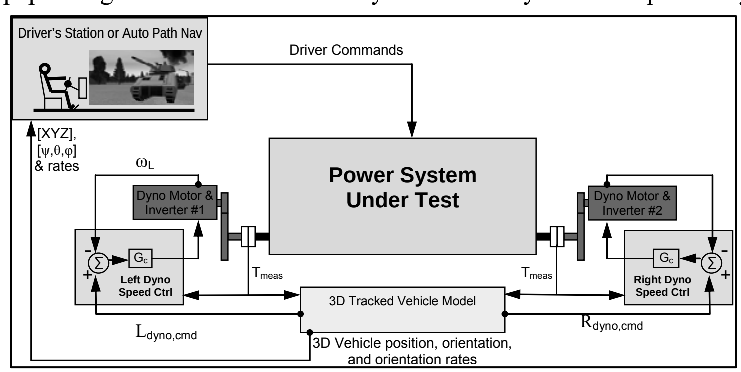


*Figure 3. Dynamometer System Upgrade*

The original P&E SIL equipment described previously[2,3] remains functional. We named this legacy equipment "Lumpy" to distinguish it from the new equipment because it is not packaged into a spatially representative envelope like HERMIT, nor is it designed to accommodate a variety of stand-alone test vehicles as is the new P&E SIL. Despite these limitations, Lumpy is still an extremely valuable test bed and has been in continuous use during most of the new P&E SIL's construction period. To make Lumpy even more valuable, it received several upgrades. The original NiCad battery pack was replaced with a 15-kWh lithium-ion system identical to one installed in HERMIT. New energy dissipaters were installed and the diagnostics and data acquisition system was upgraded. Since one of the two traction motor-dyno pairs was removed to install in HERMIT, software was added that allows virtual simulation of tracked vehicle steering using only one traction motor-dyno pair (the other traction motor being virtual.) The result is that Lumpy still provides a workhorse facility allowing us to test power management strategies, individual components and subsystems, and to conduct duty cycle experiments described later.

The original P&E SIL equipment described previously[2,3] and shown in Figure 4 remains functional. We named this legacy equipment "Lumpy" to distinguish it from the new equipment because it is not packaged into a spatially representative because it is not packaged into a spatially representative envelope like HERMIT, nor is it designed to accommodate a variety of stand-alone test vehicles as is the new P&E SIL. Despite these limitations, Lumpy is still an extremely valuable test bed and has been in continuous use during most of the new P&E SIL's construction period. To make Lumpy even more valuable, it received several upgrades. The original NiCad battery pack was replaced with a 15-kWh lithium-ion system identical to one installed in HERMIT. New energy dissipaters were installed and the diagnostics and data acquisition system was upgraded. Since one of the two traction motor-dyno pairs was removed to install in HERMIT, software was added that allows virtual simulation of tracked vehicle steering using only one traction motor-dyno pair (the other traction motor being virtual.) The result is that Lumpy still provides a workhorse facility allowing us to test power management strategies, individual components and subsystems, and to conduct duty cycle experiments described later.

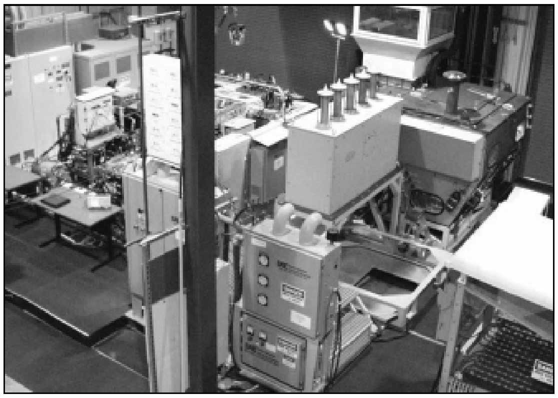

*Figure 4. Original P&E SIL (now called **"Lumpy"**)*

## HERMIT

The *Hybrid Electric Reconfigurable Moveable Integration Testbed*, HERMIT, is an FCS MGV-like hull populated with engine/generator, power electronics, control system, batteries, traction motors, inverters, and an updated thermal management system. The HERMIT mock vehicle chassis will demonstrate both size and packaging similar to an actual hybrid electric combat vehicle. Figure 5 shows a basic population plan for the HERMIT. Figure 6 shows the HERMIT during assembly. Currently, FCS is developing a chassis similar to HERMIT (simply called a "hot buck") to test MGV components. Both HERMIT and the FCS hot buck will use the P&E SIL's new dynamometers for full system testing. The FCS tests are distinct from the science and technology tests that will use HERMIT. For that reason, both HERMIT and the FCS hot buck (not described here) are stand-alone test fixtures that can be exchanged with each other in less than a day. The new P&E SIL is therefore a dual use facility; its dynamometers will provide realistic vehicle loads to both the FCS program and the TARDEC Science and Technology program. The addition of HERMIT will enable continued development and maturation of advanced hybrid components, sub-systems and systems relevant to advanced combat vehicles like the FCS-MGV.

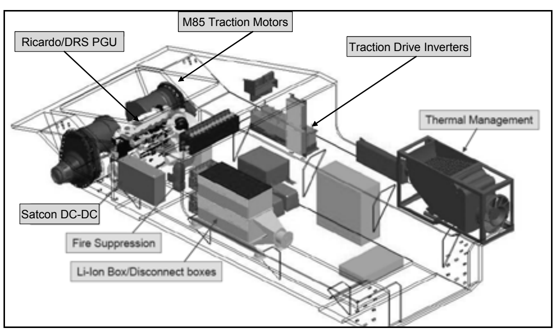


*Figure 5. Hybrid Electric Reconfigurable Moveable Integration Testbed (HERMIT) Population Plan*


*Figure 6. HERMIT During Assembly*

HERMIT is completely self-contained. All subsystems necessary for its operation reside on the HERMIT structure with the exception of driver inputs. Driver inputs such as throttle steer and brake commands are transmitted through optical fibers or wireless links. The chassis is on casters to allow ease of installation on the dynamometer test stand. HERMIT is effectively an actual vehicle; all it lacks is a suspension system, road wheels, and tracks. This feature makes HERMIT a highly relevant environment to test on-board systems. The HERMIT interior also provides a realistic EMI environment. Vehicle power distribution and diagnostics systems can be evaluated easily under highly relevant conditions in a full-scale system environment. Fuel-economy over a prescribed duty cycle will serve as a baseline for future component evaluations in the system.

A main premise of HERMIT is its re-configurability. The interior space is open to allow easy removal and replacement of components. The initial configuration will include a six-cylinder, transversely mounted, twin turbocharged

diesel engine delivering approximately 450-bhp to a DRS model PA44 permanent magnet generator and a DRS CA500 inverter. Plans are to replace this power generation unit (PGU) with a 4R890 MTU 4-cylinder engine coupled with a SatCon generator which will undergo initial testing at the Army Research Laboratories (ARL) before being delivered to the P&E SIL in late 2007. Mounting arrangements for the MTU engine are not decided yet, so HERMIT's interior spaces are designed to accommodate several configuration options. This is but one example of the re-configurable design approach. After the initial PGU is evaluated in the HERMIT, a separate PGU can be evaluated in the same hybrid electric power system.

The basic HERMIT architecture is that of a series hybrid electric drive with a nominal 600-volt DC bus. One difference between the HERMIT system and the original "Lumpy" system is the use of a DC-DC converter to step up battery voltage by a factor of two. The battery system now installed on HERMIT is two parallel, seven-module strings of SAFT VL30P lithium ion cells with 12 series-connected cells in each module. Nominal voltage is 304-volts at 3.6-volt/cell; nominal energy storage is 18 kWh. Several DC-DC converters are planned for HERMIT evaluation. The initial configuration will use a SatCon converter developed for ARL that is designed for 300-kW bursts (several seconds) and 200-kW continuously using an 80-degree Celsius coolant. Nominal input rating is 300-volts with approximately a 250-volt to 350-volt range. Nominal output rating is 610-volts with approximately a 580-volt to 640-volt range. Two other DC-DC converters are planned for future system testing in HERMIT, one developed by ARL and another by Magnet Motor. Again, the re-configurability of HERMIT lends itself to parametric investigation of various advanced components in a timely fashion.

The initial traction drive system on HERMIT is adapted from the BAE NLOS demonstrator final drive system originally installed as a motor-dyno pair in Lumpy. Each drive unit is powered by a BAE model 85 induction motor. Both motors are driven with a BAE 1900-12 "Pegasus" Inverter. The drive units connect to the AVL dynamometers with fixed length, flanged shafts. The HERMIT control system is adapted from the Lumpy system previously described and shown schematically in Figure 3. A high-fidelity, 3-D tracked vehicle model[7] sends commands to right and left dynamometer speed control units; the model also sends position, orientation and orientation rate change information to either a driver's station or an automatic path navigation module. Torque measurements from the dynamometers are fed back into the vehicle model and the dynamometer speed control units. This ability to drive the HERMIT system is essential to the duty cycle experiments described in the following section.

The HERMIT Thermal Management System (TMS), as depicted in Figure 7 allowing for alarm set-points, uses a stack of three heat exchangers to transmit waste heat from three independent propylene glycol/water (PGW) coolant loops to ambient air. The air stream is driven by a custom-built 600-volt electric fan drive. The three primary coolant loops are identified as low- (LT), mid- (MT) and high-temperature (HT) loops based upon component operating limitations and overall system functional performance. The LT PGW loop principally manages cooling loads from the component electronics and the Power Generation Unit (PGU) charge air cooler. The MT PGW loop handles cooling loads from the HERMIT Traction Drive System (TDS), exchanging waste heat with the TDS cooling circuit that utilizes automatic transmission fluid (ATF) to cool the traction inverters, motors and gearboxes. The HT PGW loop provides for cooling of the PGU engine. The HERMIT TMS also provides for real-time monitoring and logging of thermophysical states and performance data through the Low Speed Data Acquisition System (LS-DAS). The LS-DAS records temperatures, pressures and flow rates with a graphical user interface that generates real-time plots, system calculations and through an image similar to Figure 7 allows for alarm set-points and system-level monitoring.

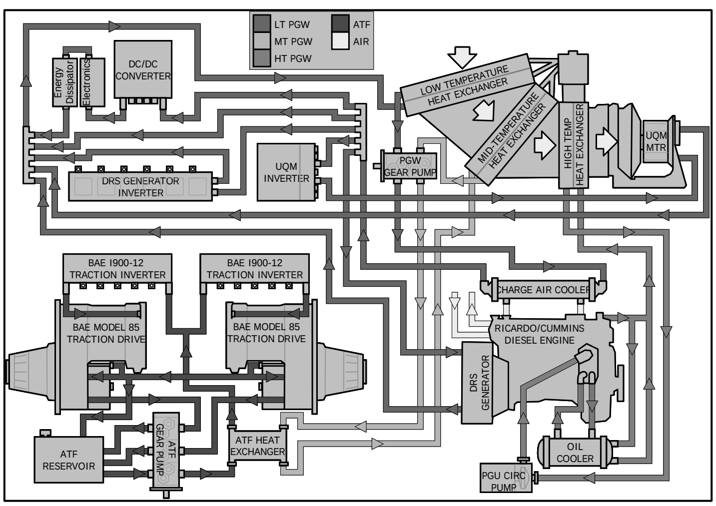

*Figure 7. HERMIT Thermal Management System (TMS)*

HERMIT is undergoing final commissioning tests at this writing. The first full system use will be to conduct the third in a series of duty cycle experiments described next.

# DUTY CYCLE EXPERIMENTS

The Army has needed a means of quickly and efficiently determining the effects of duty cycle variations on vehicle subsystems for many years. Duty cycle data relevant to realistic conditions in the field are often difficult to obtain, especially in situations where survival is at stake. Moreover, in the design process for a new vehicle it is often difficult to rely on existing use data to specify size and design of advanced components because the concept of operations and vehicle requirements differs markedly from past experience. The FCS program exemplifies such a situation. There is no use data for

vehicles operating in an FCS systems of systems environment. Intimate coupling of use history with vehicle design therefore is problematic. To address this problem, TARDEC launched a series of simulation based duty cycle experiments[8] in 2005, just after the last AECV conference. These experiments are part of an effort called Army Power Budget Model (APBM) Duty Cycle Experiments (DCE). The experiments are important because they represent a joining of several vehicle simulation and test technologies into a coherent and collaborative whole. As a result, the Army now has a new capability that will greatly assist hybrid-electric-powered and conventionally propelled combat and tactical vehicle development in the future. With this new capability, Army engineers and scientists can efficiently examine the behavior and reliability of a multitude of electrical subsystems and components in a realistic environment, under realistic usage conditions, in a variety of design configurations, all at full scale power and energy levels. The resultant ability to do rapid prototyping in the laboratory will greatly enhance the Army's ability to evaluate new technologies and will shorten the time required to place those new technologies into the hands of Soldiers who need them.

Figure 8 shows the two laboratory locations used for the duty cycle experiments. The first of these is the U.S. Army TARDEC Simulation Laboratory (TSL) in Warren, MI. The TSL includes a Ride Motion Simulator (RMS) which gives kinetic feedback to drivers, a set of Crew-integration and Automation Test-bed (CAT) crew stations for both drivers and gunners, and an Embedded Simulation System (ESS) that was designed for the CAT crew stations. The ESS provides modules that simulate major functions of a vehicle. The second laboratory location is the P&E SIL in Santa Clara, CA. In the first duty cycle experiment (called DCE 1) conducted in November-December 2005[9] the P&E SIL hardware was not used but the power system component of the P&E SIL's high-fidelity, 3-D tracked vehicle model[7] was used. The power system model (CHPSPerf) was integrated into the ESS. In DCE 1 a vignette that came from a CASTFOREM force-on-force simulation was used in the simulation. Actual drivers and gunners participated in a simulated battle in which other vehicles were modeled using OneSAF Test Bed (OTB) 2.0 software. These experiments provided calculated power train data, incorporated Soldier input into the dynamics feedback from the motion simulator, and provided overall realism and fidelity to Force on Force simulations. Results are described in Reference 7.

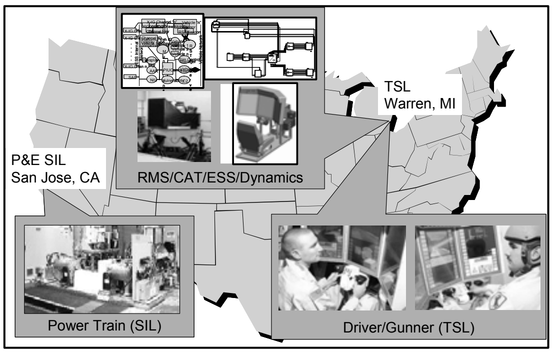


*Figure 8. Duty Cycle Experiments*

The next experiment, DCE 2, was conducted in June-July 2006[10] and added actual P&E SIL hardware to the simulation. This addition required solving several challenging problems, none the least of which is the fact that the two laboratory locations, the TARDEC Simulation Laboratory (TSL) and the P&E P&E SIL, are 2,450 miles apart. That distance causes a significant delay in signals between the two laboratories. The minimum round trip time at the speed of light in free space is 26 ms. Repeaters and other circuit elements will increase that delay. Bandwidth of the communication channel is much less important because there is a high fidelity vehicle model running at both ends. A complete human-in-the-loop/hardware-in-the-loop simulation is attainable by simply sending relatively low bandwidth throttle, steer and brake driver commands from the TSL crew station to the P&E SIL, then returning hardware data and vehicle state information back to the TSL to close the loop. This "long haul interface" is illustrated in Figure 9. The assets above the wide grey line, which represents the communication link, are those located in the TSL; the ones below the line represent those in the P&E SIL. The blocks outlined in grey are "observers" that act as the element missing in each laboratory. The Power Train Observer in the TSL provides the high fidelity P&E SIL model and the Vehicle Dynamics and Terrain Observer in the P&E SIL computes the vehicle response to the terrain model and driver inputs. In effect, two simulations run simultaneously, one in the P&E SIL and one in the TSL. The simulated elements (the observers) can then be close coupled to the hardware at each location. At the TSL the human driver issues throttle, steer and brake commands that go simultaneously to the power train observer and the P&E SIL in Santa Clara over the communication link. The vehicle dynamics and terrain model receives sprocket torque values from the observer, then generates motion commands to the Ride Motion Simulator in which the driver is located, and sends computed speed data back to the observer; it also sends vehicle position and motion rate of change information across the

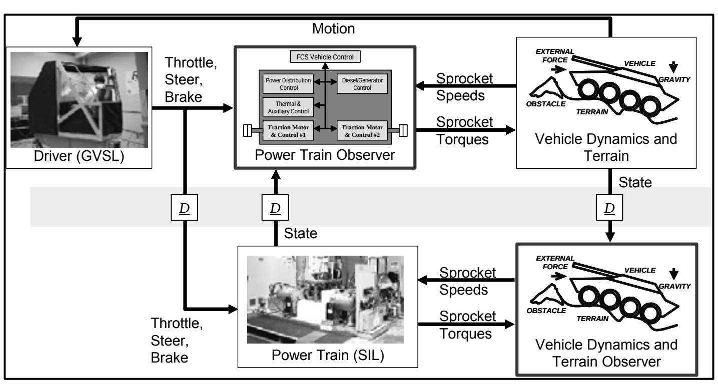


*Figure 9. Long Haul Topology Developed for DCE 2*

communication link to the P&E SIL. Meanwhile, back at the P&E SIL, the P&E SIL control system uses the received throttle, steer and brake commands to activate the power system and generate torque from the traction motors, plus it sends the torque data to the Vehicle Dynamics and Terrain Observer. The observer then activates the dynamometers in response to the programmed terrain model and state information from the TSL, and reports the sprocket speeds back to the P&E SIL power train.

Once the models and logical topology for the long haul communication are established, three more questions remain: 1) what communication medium and transport protocol should be used; 2) how to compensate for the time delay between the two laboratories; and, 3) how to ensure that the P&E SIL and TSL are tracking each other accurately in real time. All three problems are now solved, but details of the latter two are beyond the scope of this summary. Based on reliability trades that take into account the effects of data loss, engineers chose to communicate over the open internet using a UDP transport protocol. The delay compensation for single a state variable, torque in this case, is discussed in reference[11], where experimental results of using adaptive learning and Kalman filters appear. The final question arises because the two parallel simulations running at the P&E SIL and TSL do not exactly represent the real hardware and the time delays of updates over the communication channel vary. As a result, the vehicle states in the two locations will diverge over time unless some tracking means is applied to lock them together. This issue we call the "state convergence" problem. The solution to the problem is thoroughly discussed in reference[12] where two methods of solution are considered, sliding mode control and H-infinity control.

DCE 2 validated the methodology of determining duty cycles using real drivers on a motion based simulator connected to a real hardware vehicle system located in a remote laboratory. Future experiments are planned. DCE 3 should be underway at the time of the 7th AECV conference. DCE 3 will use the same basic approach as DCE 2 to collect duty cycle information, but will use the HERMIT hardware instead of "Lumpy." This set of experiments pushes the fidelity of the simulation to an even higher level.

## PULSED POWER EXPERIMENTS

The P&E SIL is unique in its capability to test full-scale hybrid electric power systems in conjunction with high-voltage, high-current pulsed power systems. Pulsed power systems will play an important role in future weapon and survivability systems because they are necessary for electric armor, electric guns and directed energy weapons. None of these advanced systems is ready for fielding yet but all are in various stages of development. It is prudent, therefore, to ensure that future vehicle propulsion systems are able to function reliably in the presence of systems that generate high-voltage, high-current pulses. The P&E SIL was built with that purpose in mind. The parameter regimes capable of being tested now include voltages up to 10-kV, currents exceeding 500-kA with pulse lengths from approximately 100-microseconds to 1-millisecond.

Two "generations" of PFNs now have been tested in the P&E SIL[3,4,5], each having more advanced features than its predecessor. Both generations are "dual pulse" designs that are capable of powering either electromagnetic armor (EMA) modules or electro-thermal-chemical (ETC) guns, depending on how they are switched. Both PFN generations have successfully demonstrated full power operation in all modes with the P&E SIL's full hybrid electric power system operating. Therefore the question of whether high-current, high-voltage pulses will deleteriously affect the electric propulsion system or vice versa is now answered. The first generation PFN (Figure 10) consisted of two subsystems, each storing 100 kJ. The two output pulse modes were produced by two separate switching systems. For the shorter pulse appropriate to an EMA load, both subsystems discharge in parallel through individual high-current triggered vacuum switches to produce a current waveform approximately 50- to 80-microseconds wide at a voltage of 10-kV. To produce the longer pulses (of order 1-millisecond) needed by ETC guns, only one of the two subsystems is discharged though a separate switch and pulse-stretching inductor.

*Figure 10. Generation 1 Pulse Forming Network*

The second generation PFN was designed and built with different purposes in mind. First of all, the modularity was increased to allow the system to produce a wider variety of waveforms. Instead of only two pulse widths. The system circuit diagram of Figure 11 shows how this variable pulse shape is accomplished. There are three "bulk modules", each with four capacitors in parallel. A combination of two parallel inductor-switch combinations is in series with each module. The inductors have different values, so in principle each bulk module can discharge with three different fundamental frequencies corresponding to whether both its switches are fired, or either of the switches are fired separately. By selecting the switch firing arrangement, the main pulse length can be varied over some range. One inductor in each bulk module is 490-nH and the other is 6,890-nH. All capacitors are rated for ~250 µF, 12.5 kV, 1.59 J/cc. The bulk modules discharge more slowly than the shaping module and form the basic pulse. The shaping module has four different inductors with values of 4,510-nH,

1,700-nH, 210-nH and a shorting bar (uses only the internal PFN inductance). To select the ETC or the EMA mode of operation, a bypass circuit is included on the output of the system. The bypass circuit is a bypass switch in parallel with an 18 μH inductor as shown in the circuit diagram. The variability designed into the PFN allows for experimental pulse shape optimization. The flexibility provided also allows for degraded performance experiments in which a disabled module is simulated by not firing its switches at all. The Generation 2 PFN is shown in Figure 12.

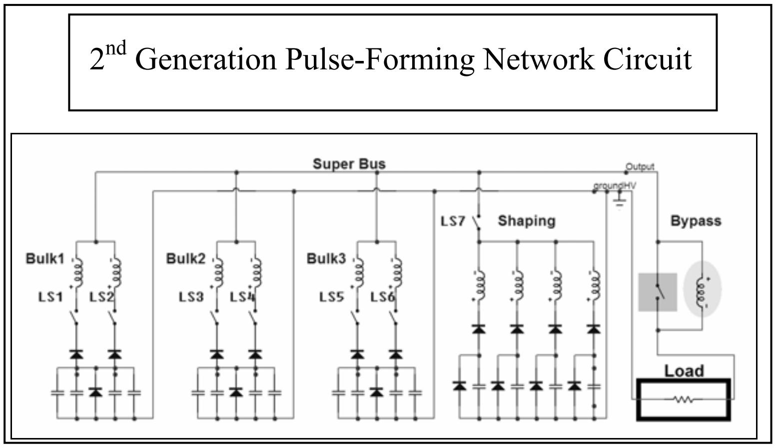


*Figure 11. Generation 2 PFN Circuit*

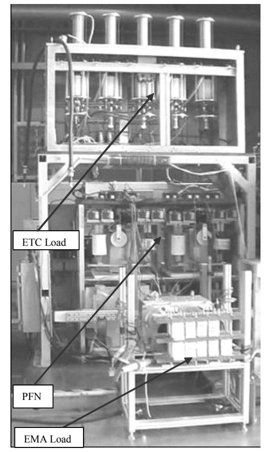


*Figure 12. Generation 2 PFN in P&E SIL with ETC and EMA Loads*

Besides the design changes that add flexibility, the second generation PFN incorporates newer pulsed power technology than was available for the design of the first generation version. The capacitor energy density is higher, 1.6 J/cc compared to 0.7 J/cc. The charging system is faster. The switches are high-current solid state varieties instead of vacuum switches. The system is more easily reconfigured. The controller is improved. Maintainability is improved. A low inductance (3-nH/ft) current bus is incorporated. The new PFN served as a test bed for many of these new design features. For example, two types of solid state switches were tested, one of which was an OptiSwitch light Activated Solid State (LASS) switch. The LASS switches are based on an asymmetrical thyristor with integrated anti-parallel diodes activated by a fiber-coupled semiconductor laser diode array. LASS switches have many advantages such as immunity to noise-induced pre-firing and easy triggering. In our tests, unfortunately, we found that the switches we obtained were unable to hold reliably more than 6-kV (the requirement was 10-kV.) For PFN testing into high power loads we used Super Gate Turn Off Thyristors (SGTOs) instead.

The SGTOs we used were developed for and tested at the Army Research Laboratories (ARL.) The benefits of SGTO switches are: the capability to withstand higher dI/dt, peak power levels and current densities; increased reliability and lifetime; and, smaller switch volume in comparison to other solid state switches. The peak current achieved by the SGTO during development was 83.3-kA; that value was verified during the 2nd generation PFN EMA load testing. ARL is collaborating with Silicon Power Corporation (SPCO), the SGTO manufacturer, and Cree Inc. (SiC wafer manufacturer) to evaluate the enhanced performance of SGTOs implemented in SiC and to improve packaging for future pulsed power applications. The cell-based SGTO approach provides for extremely high turn-on gains (with drastically reduced gate-drive requirements) and negates the need for a bulky clamping.

Once component testing and optimization were completed using the second generation PFN, the entire system was tested into two types of dynamic (time-varying impedance) loads, one for simulating an ETC gun, the other for simulating an EM armor module. Both types of load appear in Figure 12. The ETC load is shown mounted on a stand above the PFN has five canisters connected to an array of vacuum switches that serve to connect and disconnect the canisters to and from the PFN sequentially. The canisters simulate the behavior of a 60 mm ETC cartridge with inert material replacing the propellant bed. The sequential firing capability simulates an autoloader in order to test fire the PFN repetitively, as in a real battle. The load is the same one used for Generation 1 PFN testing. Likewise, the EMA load is the same as was used for Generation 1 PFN testing. The dynamic EMA load is a double-fuse device designed to simulate the time-varying impedance of an EM armor module. Testing included using the load in both a single fuse and double fuse mode to vary impedance profiles presented to the PFN. Reference 4 describes both the ETC load and the EMA load in more detail.

Results of Generation 2 PFN testing were very encouraging from the standpoint of, once again, verifying that either EM armor or ETC guns is compatible with hybrid electric combat vehicles. Furthermore, the flexibility of the new PFN allowed verifying that the degraded mode (lost modules) would not entirely prevent EMA or ETC gun operation. We completed static and dynamic EMA load tests. Both single and double fuse shots were performed at 9kV while all P&E SIL systems were operating, demonstrating the operation of the PFN & EMA load in a hybrid vehicle environment. Maximum currents of the order of 400-kA were reached. Similarly, static and dynamic ETC load tests showed the same compatibility. Both single and multiple shots were fired at 7.5-kV with all P&E SIL systems operating. These results will be presented in

more detail at a future date. For now, suffice it to say that the tests were very successful and they bode well for applications of advanced electric weapons and survivability suites in future electric combat vehicles.

## CONCLUSION AND FUTURE WORK

The U.S. Army TARDEC's Power and Energy program continues to produce valuable data and to develop new technology in support of the vision for a lighter, more lethal set of ground vehicle assets. The System Integration Laboratory in Santa Clara, CA now is a greatly expanded, multiple use facility in which ground combat vehicle prototypes or pre-production models can be tested under realistic, highly relevant conditions. Such testing will be conducted for the Future Combat System program over the next few years. In addition to expanding the P&E SIL's capabilities, a completely new vehicle system called HERMIT (for Hybrid Electric Reconfigurable Moveable Integration Test bed) has been constructed for future use. HERMIT is a complete, stand-alone testing asset that can be easily transported to other locations. Following initial testing in Santa Clara, CA, HERMIT will be moved to Warren, MI where it will undergo further testing and will be used to investigate new components and subsystems under development in the TARDEC science and technology program. A dynamometer system to allow such tests in Michigan is under preparation now. The P&E SIL in California will remain operational for FCS testing until some future date. In addition, plans are being formulated to extend the P&E SIL's capabilities to allow a wider range of vehicle tests, especially tactical wheeled vehicles.

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